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A Review on the Geotechnical and Electrical Properties of Hydrocarbon-Contaminated Soils

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Abstract

Oil contamination of the ground due to leaks in oil pipes, transportation of hydrocarbon products, or during excavation stages of oil production can alter the subsurface's physical characteristics, mechanical behavior, chemical reactivity, and electrical response. Consequently, the subsurface may become unsuitable for construction and might require significant remediation. Therefore, it is essential to gain a deep understanding of the overall attitude and the associated ground properties in case of pollution. This paper reviews the existing literature related to hydrocarbon soil contamination. The main focus is on previous studies that evaluate the geotechnical and electrical properties of subsoil after exposure to crude oil or its products. The paper emphasizes soil properties such as soil particles, Atterberg limits, specific gravity, compaction characteristics, pH value, undrained shear strength, and consolidation response. It is found that soil properties are significantly affected by contamination, depending on soil type, hydrocarbon product, and contamination proportions. Additionally, methods of soil treatment are briefly discussed.

Keywords— Soil pollution, Ground contamination, Hydrocarbons, Soil treatment

1 Introduction

The global industry sectors, Hydrocarbon products as a raw material such as crude oil, kerosene, gasoline, engine oil, lead nitrate, and diesel, which are key energy sources (AL-khyat et al., 2023) (Karkush et al., 2020) (Karkush & Jihad, 2020) In the oil industry, ground pollution may arise as a result of oil leakage of oil from broken pipes, product transportation, or during oil drilling activities(Nasr, 2013). Locally, contamination with oil products is considered one of the greatest risks associated with the marine environment, particularly in the south. Typically, there are many potential sources of leakage, including oil tankers, subsea pipelines, oil export stations, and shipping accidents. The transfer of oil from production fields to end users is fundamentally accompanied by the risk of accidental spills (Al-

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Behadili et al., 2023). Oil pollution harms soil through a combination of physical, chemical, and biological mechanisms that fundamentally alter the soil structure and poison the ecosystem.

Recently, numerous oil product leakage cases have been reported at many sites due to damage in oil industrial infrastructures, which consequently led to significant environmental hazards and deterioration of the soil and its related features (A. Al-Obaidy et al., 2019). The hydrocarbon contamination of the ground significantly affects the overall behavior of the soil, depending on the ground type and the nature and amount of the petroleum product (Elisha, 2012). The persistent occurrence of ground contamination has motivated extensive research into the impact of hydrocarbons on the geotechnical properties of coarse- and fine-grained soils, as shown in Table 1. Although researchers are making substantial efforts to develop practical methods to address this issue, soil contamination remains inevitable.

A proposal solution could include consuming contaminated subsoil after appropriate stabilization in many engineering applications, e.g., embankments, road sublayers, backfills, etc. Meanwhile, having deep insight into how the petroleum seeps into a soil stratum can change its geotechnical and electrical characteristics is crucial for assuring a trustworthy estimate on the integrity of the affected ground as a foundation material, or considering the proper remediation method (A. Al-Obaidy et al., 2019). This paper firstly reviewed the mechanism of contamination, then presented the impact of hydrocarbons on index characteristics of soil, including grain size distribution, Atterberg limits, and specific gravity. The effect of contamination on the mechanical behavior of soil has also been demonstrated, which consists of compaction, undrained shear strength, and consolidation. The impact of hydrocarbons on chemical and electrical characteristics was also illustrated in the subsequent sections. Finally, the remediation methods used to manipulate the contamination on the soil characteristics have been discussed.

Table 1: Summary of the investigations conducted on contaminated soils

Study/ Reference	Location	Soil type	Contamination %	Testing	Outcomes
Rehman et al. (Abduljauwad & Akram, 2007)	Saudi Arabia	Clay	58	Atterberg limits Compaction Shear Strength Compression and Swelling	- PI, PL, and LL increase - MDD increases -OMC decrease -The strength was reduced -The percentage swelling reduced by about 50%
Rahman et al. (Zulfahmi Ali Rahman et al., 2010)	-	Basaltic Soil	Artificial 4, 8, 12, 16	Atterberg limits Compaction Shear Strength	- PI, PL, and LL decrease -MDD and OMC decrease -The Cu values decrease
Nasr, A.M.A (Nasr, 2013)	Iraq	Sand	Artificial 3%	Uplift resistance	Uplift resistance decreases
Daka (Daka, 2015)	_	Bentonite/ Kaolinites	Artificial 1.8, 3.5, 5.3, 7.1	Gradation Atterberg limits Hydraulic conductivity Consolidation	-MDD and OMC decrease -PI, PL, and LL increase -Hydraulic conductivity decrease
Al Obaidy et al. (A. Al-Obaidy et al., 2019)	Iraq	Clayey Silty	2,5, 10	Atterberg limits Compaction Gradation Consolidation	-PI, PL, and LL increase -MDD increases -OMC decrease -compressibility increase

				Geophysics tests	-The resistivity measurements decrease
Al Obaidy et al (N. K. Al-Obaidy & Shaia, 2019)	Iraq	Clayey Silty Sandy Soil	2,5, 10	Atterberg limits Vane Shear Gradation	-PI, PL, and LL increase -Shear Strength increase -Grain size distribution curve from finer to coarser ranges.
Mekkiyah et al. (Mekkiyah et al., 2023)	Iraq	Silty loam, sandy loam	Artificial 4, 8, 12, 16	Atterberg limits Permeability Specific gravity UCS	-LL and PL increase -PI decrease -permeability decrease -Specific gravity decreases
Salimnezhad et al. (Salimnezhad et al., 2021)	Iran	Clay	Artificial 4, 8, 12	Atterberg limits Compaction UCS Direct shear Consolidation	-MDD, OMC, UCS, and the shear reduced -coefficient of consolidation decreases
Oyediran et al.(Oyediran & Enya, 2020)	Nigeria	CH	Artificial 2-1	Atterberg limits Compaction UCS Permeability Mineral composition Chemical composition	-UCS, MDD increased when the oil content was up to 4% then decreased -LL, PL, and PI increased with crude oil up to 4%, then decreased
Kermani et al.(Kermani & Ebadi, 2012)	Iran	CL	Artificial 4, 8, 12	Atterberg limits Compaction Strength	-LL and PL increase -PI decrease -MDD increases -OMC decrease -Cohesion reduces -Friction angle and compressibility increase
Alhassan et al.(Alhassan & Fagge, 2013)	Northern Nigeria	Sand, clay, and lateritic soil	Artificial 2, 4, %	Compaction Atterberg limits CBR Consolidation Triaxial test	-consolidation settlement decrease for clay and increase for lateritic soil -MDD increased -CBR of clay decreases, CBR of sand and lateritic soil increase, then decrease -shear strength increase
Oluremi et al.(Oluremi et al., 2015)	Nigeria	lateritic soil	Artificial 2, 4, 6, 8	Atterberg limits Compaction UCS	-UCS increases, then decreases -MDD decreases, and OMC increases -LL and PL decrease
Sutormin et al.(Sutormin et al., 2024)	in Western Siberia's	podzolic, sod-gley, and alluvial	5, 10, 15	-pH Measurement -Cation Exchange Capacity	-pH increase -CEC in podzolic soils dropped fivefold

	middle taiga			-Capillary Moisture	-the most pronounced decline observed in alluvial soils' capillary moisture levels
Ali, S. et al. (Ali et al., 2024)	Pakistan	Clay, Sand	-	-Atterberg limit -Direct shear strength -Sieving analysis -Consolidation -Unconfined compression	-LL and PL increase -PI decrease -shear Strength decrease -Poorly graded -Internal friction angle decrease -Cohesiveness decreases

2 Mechanisms of Contamination

Contamination hazards can include geo-environmental engineering because of its impacts on air, water, and soil. Hydrocarbons penetrating the subsurface may be trapped within the unsaturated zone or can spread, reaching the water table in the saturated zone, leading to water pollution. The trapped amount of soil can evaporate and cause air pollution. The contamination can deteriorate vegetation and consequently affect human health (Swaroop & Rani, 2015). In addition, the pollutant oil is retained in the soil pores, altering the performance of the soil (Singh & Singh, 2008) . This movement and partitioning into dissolved, liquid, and gaseous phases highlight the complexity of managing and remediating hydrocarbon spills. If crude oil is introduced in an adequate amount, there is a chance to infiltrate into the subsoil and form an NAPL mass at the underground water level. The frequency and degree of infiltration will rely on the ground characteristics (void ratio, pore size, degree of saturation) as well as the physical properties of the spilled oil (volume, viscosity, density, surface tension) Spilled oil will penetrate the soil to a point where the NAPL head is being not enough to resist pore entry pressures, and excess migration terminates. As such, the volume of migrated NAPL reduces as immovable residual NAPL is left behind due to the capillary effect (Almaliki et al., 2025).

3 Effects on physical properties

In this paper, the literature that took into consideration the impact of pollution on the engineering properties of soil, such as soil particle size, Atterberg limits, and specific gravity, will be subsequently discussed.

3.1 Grain Size Distribution

Many investigators explored the consequences of lubricant pollution on aggregate size distribution for both fine and coarse soil. For example, Ijimdiya (Ijimdiya, 2012). Investigated this effect on brown soil sediment collected from a location at Zaria in Nigeria. The soil-dominant clay mineral was kaolinite with 87% of silt. Different proportions of the pollutant (1, 2, 3, 4, 5, and 6%) were added to the dry soil sample. The results exhibited a noticeable shift in the distribution curve, moving from a finer range to a coarser range.

Recently, a similar behavior was observed by (A. Al-Obaidy et al., 2019). During the performance of the sedimentation test for a fine soil brought from a location in the south of Iraq, in Thi-Qar Governorate. In contrast to non-polluted samples, the overall trend indicated that increasing oil content moves the particle size spreading curve from finer toward coarser boundaries.

The soil particles displayed relatively rapid sedimentation at the hydrometer base and were in direct proportion to the contamination intensity, particularly with specimens comprising 10% crude oil, see Figure 1. The investigators clarified the reason behind this shift in particle size to the development of lubricant oily soil lumps in the presence of petroleum contamination (Daka, 2015).

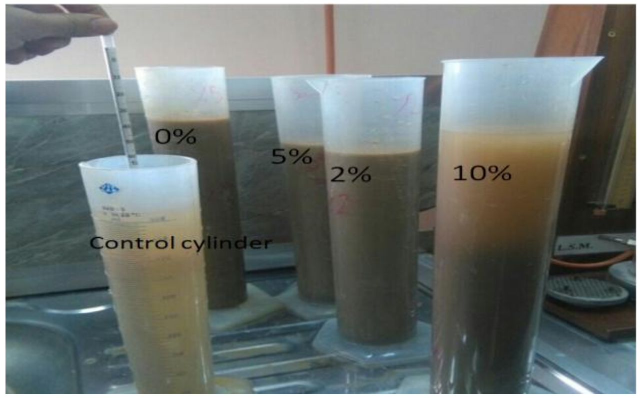

Figure 1: The hydrometer tests of the polluted soil (A. Al-Obaidy et al., 2019)

3.2 Atterberg Limits of Oil-Polluted Soils

Some researchers (Abduljauwad & Akram, 2007) (Zulfahmi Ali Rahman et al., 2010) (Granitic, 2011) explored the consistency boundaries of hydrocarbon-polluted high plasticity clay. The soil, through their study, was allowed to air dry, crushed, and pulverized through a sieve with openings of 0.420 mm . It was clear that once crude oil had been added, the Soil plasticity limits enlarged due to the development of apparent cohesion, strengthening clay particles . Bonds Atterberg limits of a low plasticity clay, which encompasses kaolinite, were examined by Khosravi et al. (Khosravi et al., 2013) in the presence of oil at different amounts (2, 4, 6, 12, and 16%). The results, as shown in Figure 2, indicated an increase in the pollution from 2% to 12%. Nevertheless, an observed drop in the subsoil plasticity limits for the range of oil content between 12% and 16%. The plasticity index decreased by approximately two-thirds under oil exposure (Karabash et al., 2023) . The liquid limits for contaminated specimens for silty loam and sandy loam recorded a decrease of 38% and 16% (Mekkiyah et al., 2023). In a more general sense, and based on an overall look at some relevant research (A. Al-Obaidy et al., 2019) (Elisha, 2012) (Abduljauwad & Akram, 2007) (Nasr, 2013) (Zulfahmi Ali Rahman et al., 2010) (Daka, 2015) (N. K. Al-Obaidy & Shaia, 2019) (Mekkiyah et al., 2023) (Oyediran & Enya, 2020) (Kermani & Ebadi, 2012) (Oluremi et al., 2015). The authors are not able to find a comprehensive trend describing the effects of hydrocarbons on these limits. There has not been a comprehensive study focusing on this subject. As it is highly dependent on soil/hydrocarbon characteristics, it is highly suggested to carry out appropriate research concentrating on the effects of hydrocarbon contaminants on the Atterberg limits of different types of soil.

The previous results were confirmed by Al-Obaidy et al., 2019, who prepared artificial contaminated samples with crude oil. Findings related to consistency limits reported that the liquid limit, plastic limit, and plasticity index increased considerably for the contaminated specimens when compared to non-contaminated specimens. Though as the oil amount in the contaminated sample upsurges, both the liquid limit and plastic limit expressed an insignificant growth, whereas the plasticity index remained basically unaffected.

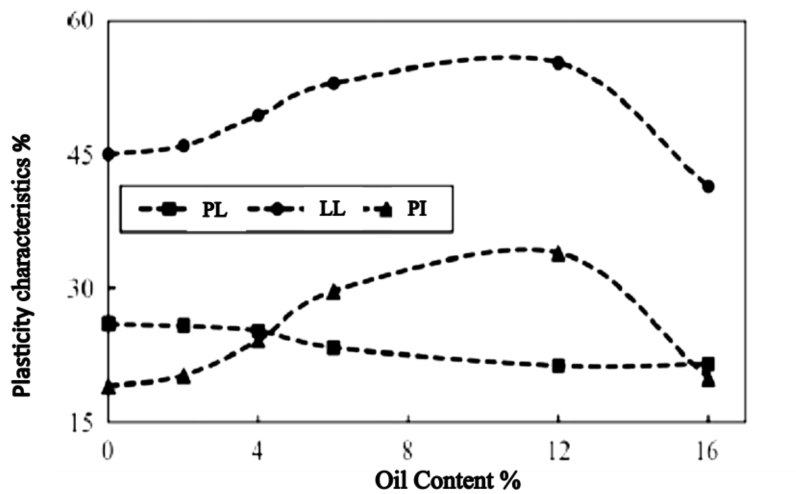

Figure 2: Atterberg limits of low plasticity polluted clay (Khosravi et al., 2013)

3.3 Specific Gravity Gs

Harsh et al. (Harsh et al., 2016) , after conducting their experimental program, they stated the general trend of specific gravity Gs to decrease as crude oil contamination increases, for both sands and kaolinite clay. This is because oil has a lower specific gravity than soil; therefore, oil occupies soil pores and may coat its particles. Thus, Gs of sand decreased by 15.44%, 29.73% and 40.54% at levels of 3%, 6% and 9% of crude oil addition, respectively. While the Gs of Kaolinite Clay exhibited a decrease of 14.3%, 32.71% and 50.1% at 3%, 6% and 9% of contamination, respectively, see (Figure 3). Moreover, Table 1 demonstrates some results of the specific gravity (Gs) for different soil types found in recent literature. Results ranged from 2.6 to 2.7.

Table 2: The specific gravity (Gs) of some types of soil

The Reference	Soil Type	Gs value
Ijimdiya (2013)	Reddish brown	2.69
Daka, (2015)	Sand	2.64
Daka, (2015)	Bentonite	2.65
Daka, (2015)	Kaolinite	2.60
PRADEEPAN (2016)	Clay	2.7
Karkush and Altaher (2017)	Clay silt	2.62-2.72
Al-Obaidy et al., (2019)	Clay silty	2.7

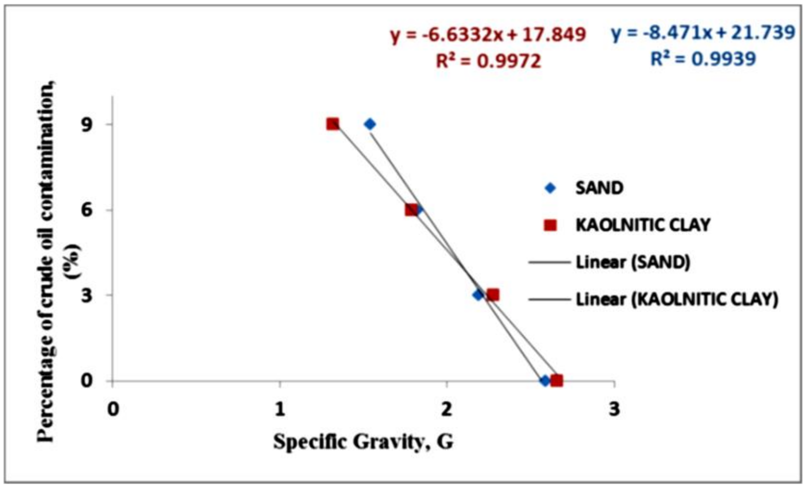

Figure 3: Specific gravity vs. % of contamination (Harsh et al., 2016)

4 Effects on mechanical behavior

4.1 Compaction Characteristics of Oil-Polluted Soils

The previous studies showed that when oil-polluted soils were compacted, the compaction features of the soils varied because the soil composition differed. It showed that the maximum dry density increased with an increase in oil content, when (A. Al-Obaidy et al., 2019) (Abduljauwad & Akram, 2007) (Zulfahmi Ali Rahman et al., 2010) compacted high plasticity clay, metasedimentary, and fine soils, respectively. The compaction curve changes to a double peak curve with a reduction in maximum dry density of 6% due to oil contamination (Karabash et al., 2023). Conversely, the maximum dry density diminished with increasing oil percentage, as reported by Abduljauwad & Akram, 2007) Zulfahmi Ali Rahman et al., 2010) (Al-Sanad et al., 1995) (Khamehchiyan et al., 2007) who conducted their experiments on compacted soils involving poorly graded sand, sand containing 5–15% silt, low-plasticity clay, and basaltic soils. Oil contamination was found to cause a reduction in both the maximum dry density (MDD) and the optimum moisture content (OMC) (A. Al-Obaidy et al., 2019) . Figure 4 visualizes the results of the compaction tests (Salimnezhad et al., 2021), which identified an increase in density versus a reduction in optimum moisture content.

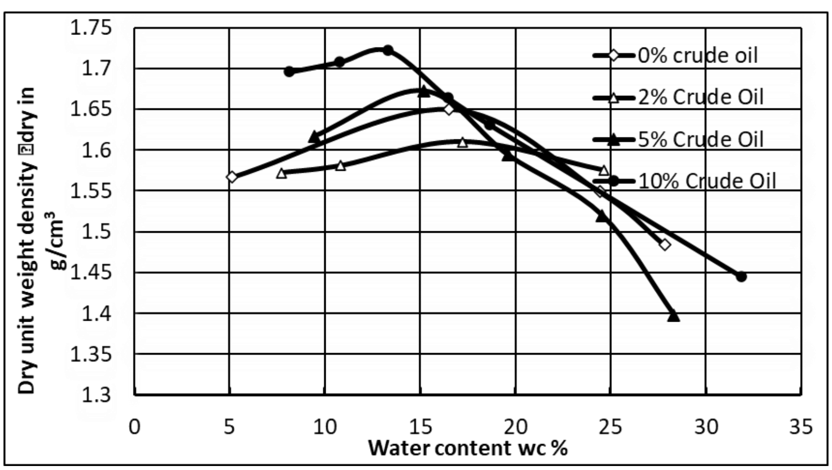

Figure 4: Compaction curves (A. Al-Obaidy et al., 2019)

4.2 Undrained Shear Strength of the Polluted Soil

Rahman et al.(Zulfahmi Ali Rahman et al., 2010) examined polluted soil specimens using a triaxial compression test to study the shear strength parameter. Three confining pressures were applied (140, 280, and 420 kPa). Unconsolidated undrained material was considered. The stress–strain relationship displayed that the uncontaminated soils attain a greater deviator stress if compared to that associated with the oil-polluted soil. The undrained shear strength USS parameters of a clay silty soil were analyzed by Al-Obaidy and Shaia (N. K. Al-Obaidy & Shaia, 2019). A vane shear test has been conducted using a hand four-bladed tester; the latter was pushed into the soil, and the vane was afterward rotated at a constant rate until the subsoil specimen failed in shear, and the corresponding torque caused the shear failure was recorded. From which the value of USS was obtained. Findings, which are visualized in Figure 5, indicated an increase in USS in accordance with increasing the oil content. However, the small dosage corresponding to 2% contamination experienced a decrease. That increase in USS could be attributed to the developed bonds among subsoil particles, and USS of the subsoil decreased once the oil was introduced, perhaps because of the lubrication caused by the oil (N. K. Al-Obaidy & Shaia, 2019).

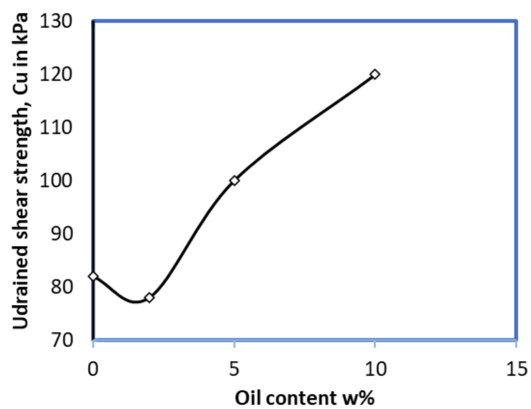

Figure 5: The USS of subsoil according to the vane shear test at diverse amounts of contamination (N. K. Al-Obaidy & Shaia, 2019)

4.3 Consolidation Characteristics

AL- Obaidy et al (A. Al-Obaidy et al., 2019) claimed that the consolidation results using the conventional test using the oedometer could not reflect the actual consolidation characteristics in the field because of the test procedure, including submerging the contaminated sample with water before applying the load, causing the discarding of a considerable amount of oil outside the sample before applying the load, making the test not reliable. Figure 6 displays the consolidation characteristics of the soil samples upon contamination.

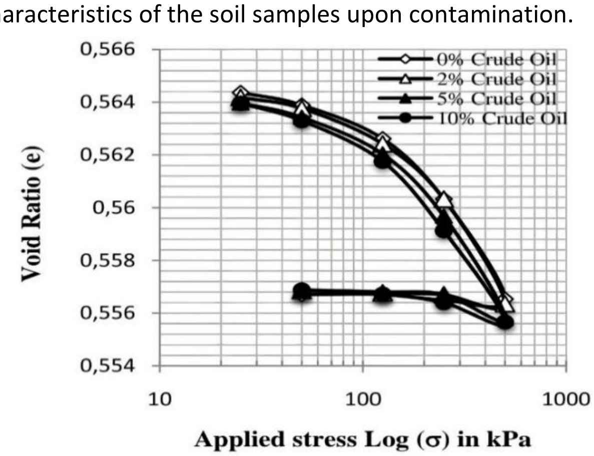

Figure 6: Consolidation characteristics upon contamination (Elisha, 2012)

5 Electrical and chemical responses

5.1 PH-Value

Soil pH can significantly influence the phase and conduct of other chemicals existing in the subsoil. It is consequently recommended that soil pH be measured whenever other chemical components, particularly metals, are to be evaluated. The soil pH is usually determined to evaluate the oil pollution, specifically when a treatment was adopted. Figure 7 shows the variation in the pH. Values after Combined Electrokinetic Soil Flushing and Bioremediation were adopted by Rodrigo et al. (Sirés et al., 2014).

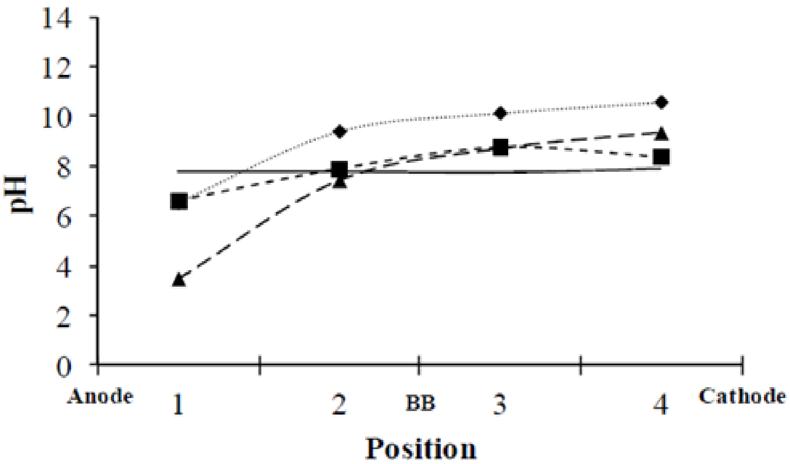

Figure 7: pH variation for different types of treatment (Sirés et al., 2014)

In Iraqi literature Karkush and Altaher , 2017 examined the pH. Measurements for subsoil specimens collected near the Thi-Qar oil refinery plant in southern Iraq, near Al-Nasiriyah city, and the associated results as a function of the elapsed time are displayed in Figure 8 .

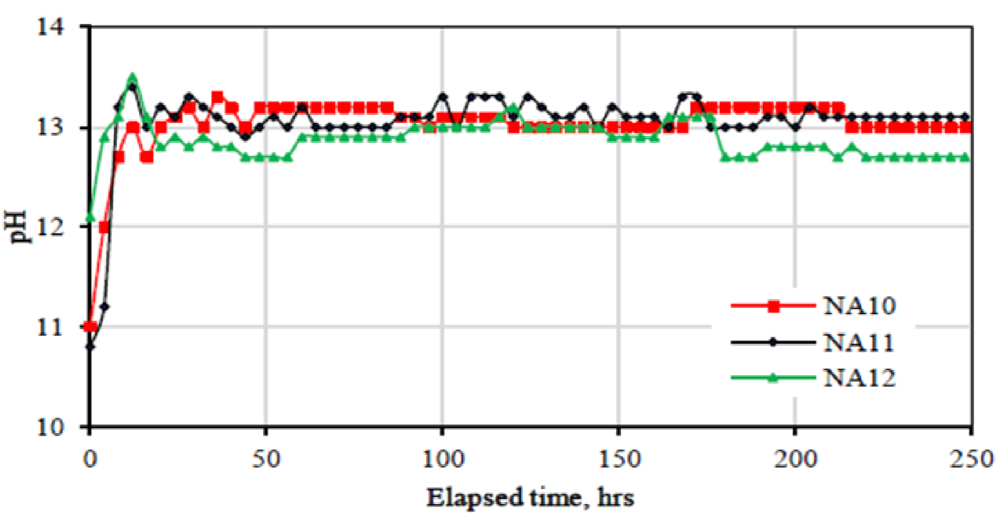

Figure 8: Variation of pH with time for three different samples (Karkush & Altaher, 2017)

5.2 Electrical Resistivity ER

Investigators were offered the electrical resistivity ER scheme as a powerful tool in their related experimental and field studies in detecting variations in geotechnical characteristics (Al-Shueli et al., 2022). Recently, others reported a correlation between the electrical resistivity ER measurements and the oil magnitude of the contaminated subsurface. The Authors attributed this connection to the electrical conductivity of petroleum substances, which is significantly different from that of the underground water. Thus, the ER characteristics of oily contaminated ground would be dissimilar, corresponding to the oil category and content (Karkush et al., 2013). Al-Obaidy et al. (Al-Shueli et al., 2022). Investigated the electrical response for soil mixes artificially polluted with crude oil at different percentages ranging between 0% and 25% of the soil dry weight. Findings showed that ER decreased considerably in the presence of oil, and the drop was noticeably higher for the soil samples categorized within lower swelling potential. Al-Obaidy and Al-Shueli (N. Al-Obaidy & Al-Shueli, 2020). utilized the ER technique to evaluate the electrical characteristics of two locations located at Thi-Qar city, south of Iraq. Samples were collected from heavily hydrocarbon-contaminated locations by crude oil. The influence of variation in the moisture content and soil densification on the ER response was investigated to replicate the potential disparities of hydrological and structural circumstances in the oily field. Findings provided actual ranges of the ER values of both sites and showed that the ER is more ruled by subsurface category and nature, despite the intensity of contamination.

Al-obaidy et al.(N. K. Al-Obaidy et al., 2020). Developed a four-electrode ER box to experimentally measure the ER of artificial expansive and non-expansive subsoil samples contaminated at various fractions of crude oil, see Figure 9 . Findings indicated a decrease in ER with increasing swelling index of non-oil-treated samples. Authors interpreted the sharp drop in ER as a possible enlargement in the surfaces of charged bentonite of fine particles. Furthermore, the increase in ER for treated oil samples was considerably higher for the expansive soil with a higher swelling index as a result of the expansion in the soil volume after inundation with water, causing a larger cross-section of the non-conductive oil compared to the lesser cross-section corresponding to samples with a lower swelling index. Two samples were taken, one with high specific gravity and the other with low specific gravity. It was observed that there was a clear increase in the apparent electrical resistance with the increase in crude oil content from 0% to 25%. And the explanation for that is that crude oil is a non-conductive (insulating) material. When added to the soil, it replaces water or coats the conductive soil particles, reducing the soil's ability to conduct electric current and increasing its resistance Figure 10. In Figure 11, the results for two soil samples with the same swelling index (FSI) value of 240 are presented and with different water content. It was found that the water content: as the water content (the conductor) increases, the resistance significantly decreases.

Figure 9: Electrical setup for a four-electrode resistivity soil testing box (N. K. Al-Obaidy et al., 2020)

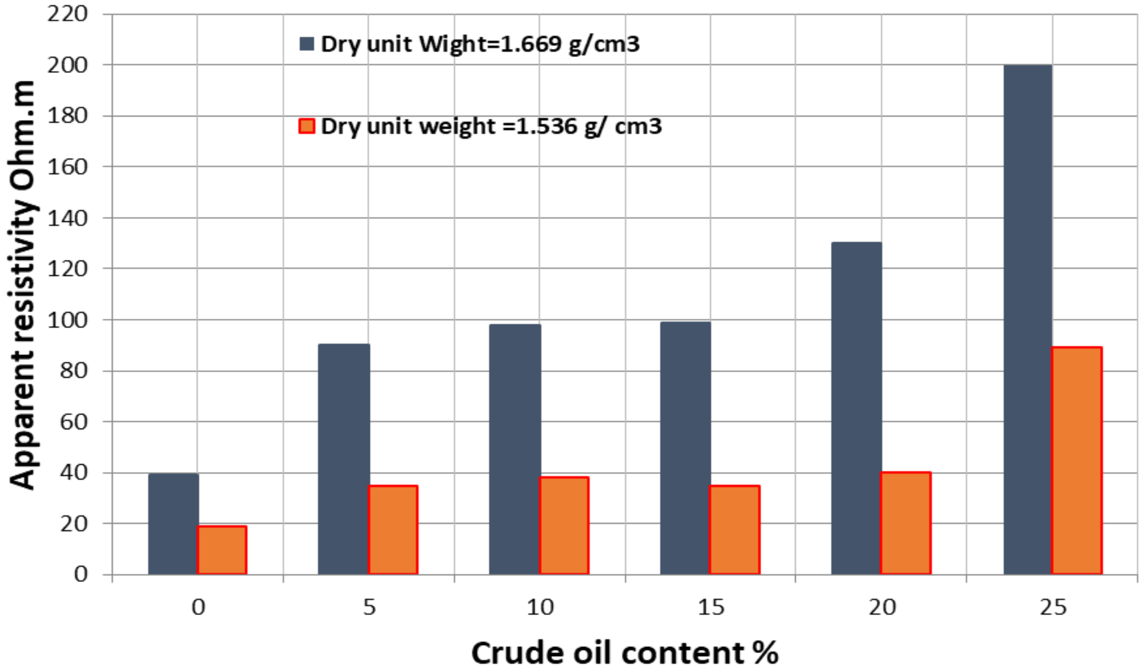

Figure 10: Apparent electrical resistivity versus crude oil content for two samples having 240% FSI and two different unit weights (N. K. Al-Obaidy et al., 2020)

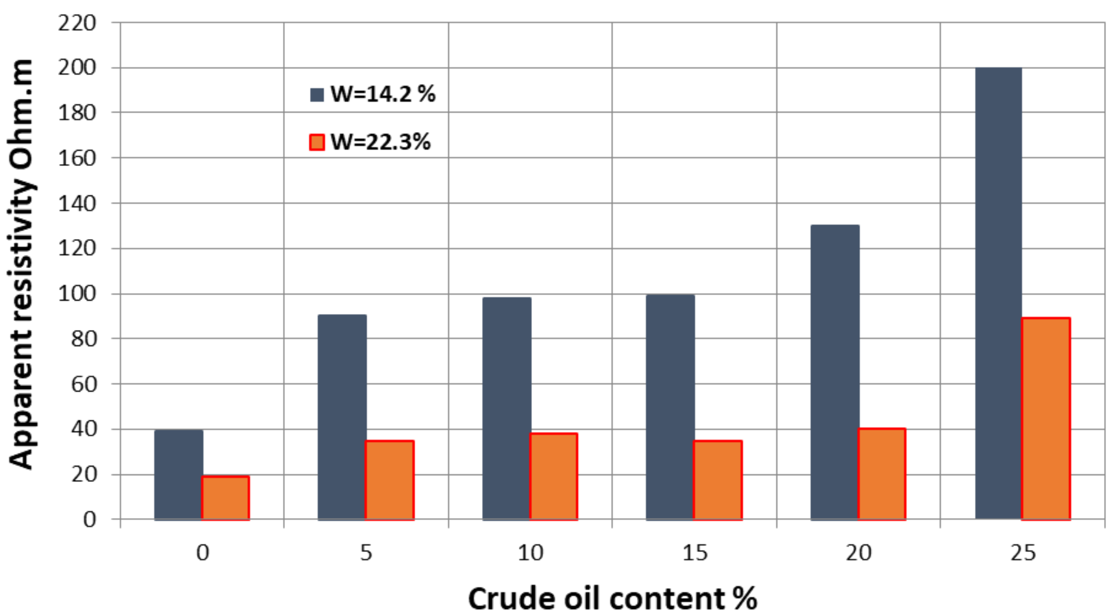

Figure 11: Apparent electrical resistivity versus crude oil content for two samples having 240% FSI and two different water contents (N. K. Al-Obaidy et al., 2020)

6 Remediation Methods

Numerous treatment guides were followed for recovering a polluted soil with petroleum, including Bioremediation, which represents a process of microorganisms, such as bacteria, to degrade pollutants in soil. From the perspective of hydrocarbon contamination, the microbes break down hydrocarbons into less harmful substances. The second remediation, including thermal desorption that utilizes heat to a certain degree for the physical separation of hydrocarbons and removes contaminants from the subsoil. The third potential treatment is soil vapor extraction; there are numerous encouraging results in decreasing the volume of treated heavy metals. However, this technique cannot reduce their toxicity. The fourth method is soil washing, which has experienced an efficiency in treating pollutants in the soil matrix. Also, Soil Purging can contribute to removing pollutant substances from affected soil based on lab experiment results. Moreover, the technique of washing-enhanced electrokinetics to remediate clayey soil contaminated with copper sulfate is also used by some researchers (Karkush & Ali, 2019). In addition to the deep mixing method for remediation of the contaminated soil (Karkush & Abdulkareem, 2019). Finally, electrokinetics is a method that includes applying a direct electric current across electrodes implanted into the subsoil to remove pollutants. Even though it is more appropriate for heavy metals and ionic impurities, it can also assist in removing hydrocarbon products under specific situations, particularly when combined with surfactants or bioremediation.

7 Research gaps and future directions

In spite of the experimental studies investigating the impact of hydrocarbon contamination on soil physical, mechanical, electrical, and chemical properties, still gaps that require attention. Lack of field-scale or laboratory consolidation data, such as compression index Cc and coefficient of consolidation Cv for naturally oil-impacted soils. In addition, available studies do not correlate ER data with consolidation or settlement in the term. New procedures or a modified oedometer are desired to measure consolidation properties without expulsion of hydrocarbons. Also, conducting simultaneous consolidation and ER measurements is recommended.

8 Conclusion

This paper reviewed the literature of previous studies related to the subject of soil contamination with oil products. The effect of contamination on the engineering and electrical characteristics was reviewed. Also, methods of remediation of the polluted soil were briefly explained. The review emphasizes the impact of oil pollution on all soil properties depending on soil type, oil product, and degree of contamination. The affected properties included soil particle size, Atterberg limits, specific gravity, compaction characteristics, and pH. Value, undrained shear strength, consolidation characteristics, and electrical resistivity.

It was concluded that the contamination changes and alters the engineering characteristics of soil. The assessment of the effect of hydrocarbonate on each soil parameter, such as grain size distribution, Atterberg limit, consolidation, and shear strength, has been discussed. The hydrocarbonate may increase both the liquid and plastic limit, and the grain size distribution is modified. These two effects added a positive sign to the modification of the consistency of the soil and workability. With respect to undrained shear strength, the percentage of contamination may give different indications. The undrained shear strength decreased at a small level of contamination, while it increased at high levels of contamination. The increase in strength may be attributed to the developed bonds among subsoil particles, which decreases the pollutant in the soil because of the lubrication caused by the oil.

The effect of hydrocarbonate on the soil parameters may arise in two fields: the first related to engineering and the second related to the environment. Due to the effect of contamination of soil, the soil parameters become unreliable, which reflects on the foundation design. The previous studies on the remediation of contaminated soil appear to show a contrast and inconsistency in the assessment of contamination impact based on the level of contamination and the composition of hydrocarbons.

The aforementioned presented gap in the research could be handled by improving the testing methodologies and long-term testing for the hydrocarbon region. Improving the remediation methodologies by integrating both engineering and environmental will contribute to the sustainable development of the region contaminated with hydrocarbons.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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